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The Application of Conceptual Models in NWP

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The Application of Conceptual Models in NWP

An evaluation of conceptual models of cyclogenesis and a preliminary study of their application in Numerical Weather Prediction.

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Abstract

Just as the human body is commonly perceived as a whole, it is best diagnosed as the sum of component parts which interact in characteristic ways independent of the overall nature of the body. In the same way, conceptual models of cyclogenesis represent the physical processes that occur within weather systems as a number of relatively precisely defined component elements that interact in characteristic ways independent of the class of cyclone. The aim of this report is to explore ways in which conceptual models may be used to improve the performance of the UKMO Unified Model by exploiting their property of exposing the anatomy of a system. The report does not aim to deal with technicalities or specifics of particular NWP procedures, but rather to perform thought experiments as to the feasibility of the proposed applications and to stimulate further investigation if appropriate.

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1. Conceptual Model Evaluation

1.1 Introduction – Conceptual models of weather systems and their origins.

Conceptual models are a blend of observational, experimental and mathematical studies made over the past 60 years, and have evolved into simplified images of complex physical systems. Although the use of conceptual models by forecasters in the interpretation of satellite imagery is a well established success, their use in other areas of weather forecasting is considerably less exploited. This preliminary report aims to address this issue, and to propose applications of conceptual models in the Met. Office Unified Model (UM).

Before the application of conceptual models is considered however, it is important to evaluate their origins: it would be disastrous to devise cunning modifications of the UM only to find that conceptual models were fundamentally unsuitable.

The evaluation to follow therefore considers three main aspects of conceptual model origins.

- **Conceptual model sources** – the '*study space*' from which information has been drawn.
- **Conceptual model synthesis** – the *'blending of information'* from a variety of cyclones with discernible characteristics.
- **Conceptual model fabric** – the '*ingredients*' forming the fabric of the conceptual model.

Thus information of various forms is merged and blended to produce a structural model of the weather system.

1.2 Conceptual Models Sources

Conceptual models draw upon studies of cyclogenesis from a variety of circumstances. For example, Evans et al. (1994) uses the term 'Rapid Maritime', Young et al. (1987) refers to the cyclones under study as 'rapidly deepening', whilst in their investigation into the structure of a frontal cyclone, Browning and Roberts (1994) studied a cyclone that was 'intense but not exceptionally so' and 'was not large and did not undergo explosive cyclogenesis'. However, it is true to say that much of the knowledge built up about the structure of cyclones comes from the study of *rapidly deepening* depressions, where 'rapidly deepening' refers to the rate at which the surface pressure drops in a developing cyclone.

The question then arises as to how common such cyclones are - for conceptual models built around studies of cyclones which occur infrequently may be of little use to NWP. It is suggested that cyclones that are rapidly deepening have structural features which are in common with the more 'ordinary' variety, but which are more prominent and therefore easier to study: it is unlikely that rapidly deepening cyclones will bear little or no resemblance to the more common variety.

1.3 Conceptual Model Synthesis

A second important consideration regarding the source of conceptual models arises when one addresses the differences in the way in which a cyclone may form in its early stages. Much work has gone into this problem over the years which has led to the development of various cyclone classification schemes. These schemes assume that there exist characteristic differences in the structure and evolution of depressions and assume that there are specific types of cyclones that can be identified. Such an approach can never hope to cover all aspects and all possibilities of cyclone development, and so naturally there are some cyclones that are 'unclassifiable' in that they possess many characteristics of more than one classification. Also, case studies have shown that it is possible for a cyclone to begin its development as one type, but develop along the path of a second entirely different type. A cyclone may therefore begin as a 'split flow' category of Youngs scheme, but subsequently develop characteristics of a 'meridional trough' type (Bader et al., 1995). This suggests that the boundary between the classifications is in practice not a rigid one as classification schemes suggests, but is more 'fluid' in nature.

Both of these problems are overcome by viewing Young's scheme solely on the interaction between the dry intrusion airstream (J2) and a jet streak (J1) associated with the polar front cloud band (P), (see Semple (1998) for the full scheme, and also Browning and Hill (1985) and Zillman and Price (1972) for similar approaches). With this approach, an attempt has been made to explain the characteristic differences between cyclones as arising from different evolutionary routes along which the cyclone can develop - the route being determined solely by the distance apart of J1 and J2, and the degree of development of a cold air feature (C) at the leading edge of J2.

The importance of this approach was to illustrate that as far as conceptual models of cyclones and their application to NWP is concerned, the important information is not what type the cyclone is, but rather the location and intensity of individual components within the cyclone (the jet streaks and the conveyor belts). It also has the advantage that cyclogenesis is viewed from the perspective of the *initial atmospheric conditions*. It is during these early stages that the UM and conventional data assimilation processes have a more difficult task in representing developing cyclones since more mature systems are larger in depth and horizontal extent and consequently easier to depict. In this context the problems of classification addressed above do not arise, and the rigid 'quantised' nature of cyclogenesis is de-emphasised.

1.4 Conceptual model fabric

The information on which conceptual models are based originates from a number of different sources. The most notable of these are

- **Observational (Qualitative) Studies.** Intuitive interpretation of observations e.g. satellite imagery.
- **Experimental (Quantitative) Studies.** Measured physical quantities from either routine or field experiment, e.g. from radiosondes and rain radar.
- **Objective analyses.** Analyses of model results *entirely based on the application of physical and dynamical principles*, and in which model imperfections are neglected.
- **Subjective analyses.** Analysis of model results in which the *judgement of a forecaster plays a significant part*, and in doing so takes into account model imperfections and a forecaster's training and experience.

A conceptual model may be derived drawing from one or more of these aspects. For example, subjective and objective analyses of model fields may be used to determine major airflows within a system that has been identified and tracked using observational studies of satellite imagery. Experimental data then may be used to better determine the distribution of cloud and rain in the system.

The use of experimental data is a purely objective exercise and should involve no preconceptions on behalf of the analyst. In some ways this is true of observational studies although the interpretation of satellite imagery goes well beyond simple pattern recognition and so it is at this stage that the human perception of the physical system is introduced.

Both subjective and objective analyses of model fields are dependent on existing models of the atmosphere (e.g. UKMO's UM), which may lead one to the view that the use of conceptual models to *improve* the existing model is rather incestuous. However, it should be emphasised that the final conceptual model contains *more* information (from experimental and observational studies, and from higher resolution of some models) than the original model output. This additional information incorporates processes which due to their complexity, are *currently either insufficiently represented or completely neglected in the UM.* The fact that conceptual models use existing numerical models is therefore an advantage, since this provides a common foundation between them and the UM. The use of conceptual models in NWP therefore potentially offers a means by which the representation of extra-tropical cyclones may be improved in the UM.

1.5 Summary

Conceptual models provide a powerful means of selecting additional meteorological information and blending it into a flexible framework of component elements. Their origins lie not in obscure physical phenomena, but in common processes that occur in all extratropical cyclones. It is these principles that go into making conceptual models ideally suited to improving the UM in aspects where inaccuracies arise, and prompt this investigation into their potential applications.

This report is designed as a preliminary study into the application of conceptual models in NWP. In view of this, key points in the forecasting process such as data assimilation, analysis fields, forecasting products and verification techniques are considered, but the does not (on the whole) deal with specific inaccuracies reported by users such as forecasters at NMC. Should the application of conceptual models be investigated beyond the confines of this report, then the consideration of specific errors appropriate to that application would be the natural next step.

2. Possible Applications of Conceptual Models in NWP

2.1 Overview

The basic premise is that conceptual models may be used as

- A Unified Model verification tool.
- A proxy for real observational data where none is available.
- A means of converting imagery information into a three-dimensional model field.

An investigation based on these principles leads to a number of proposals of ways in which conceptual models may be applied in NWP.

- ***UM verification and guide to UM development.*** Satellite imagery and conceptual models may be used to verify the representation of weather systems generated by the UM. This will not only highlight UM errors, but will serve as a tool to guide UM development.
- ***UM Skill scores.*** The identification of model errors may be useful in itself as a means of producing an indication of UM performance, perhaps with the creation of *conceptual model indices.*
- ***Interpolation of sparse observational data.*** Data received from the observational network may be interpolated or verified by conceptual models before incorporation into the model.
- ***Satellite imagery assimilation.*** Through a comparison with conceptual models, the satellite image may be reduced to its component airflows. This produces a consistent three dimensional model field which may be introduced into the UM where due to sparse observations, entire systems may be missing or mislocated.
- ***Enhancement of mesoscale structure.*** Conceptual models contain mesoscale information about weather systems that may be deduced from synoptic scale observations.
- ***Potential Vorticity (PV) inversion.*** A satellite image may be directly related to the position of airflows and PV gradients through the use of conceptual models, and this provides a sound basis for the technique of PV modification/inversion.
- ***Accounting for lower tropospheric development.*** The process described above may be extended to the lower troposphere through the use of conceptual models and the relationship of the warm conveyor belt to PV. This provides a *complete* modification of the troposphere through the use of water vapour imagery.

The first two ways consider how the existing model process may be left unchanged, but how conceptual models may be used to provide a useful way of assessing its performance or identifying imperfections, thus guiding UM development. The following five proposals deal with ways in which additional or more representative input may be provided to improve the UM analysis fields. The distinction between the two is illustrated in Figure 1, and each proposal will be dealt with in more detail in the following sections.

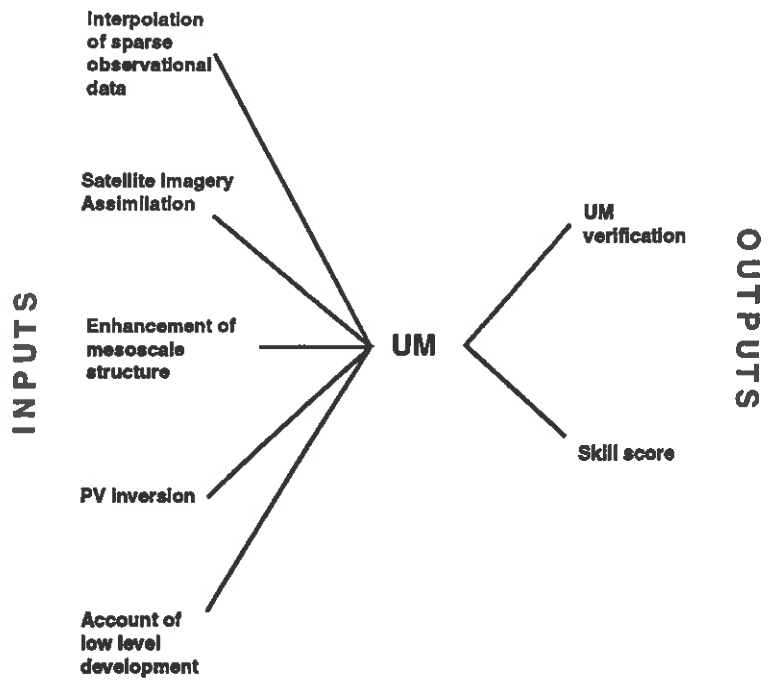

Figure 1 7 proposed ways of using conceptual models in NWP. Two proposals utilise the UM output, whilst five proposals deal with improving the analysis fields of the UM.

Many of these proposals are either interrelated or are aspects of similar principles. Although they are presented as independent applications, it is anticipated that some may be able to be used in conjunction with each other. This would increase the power and versatility of any applications.

2.2 Applications of Conceptual Models to aid in the development of NWP

2.2.1 UM Verification and Guide to UM Development

An error often encountered by forecasters (Young, 1997) is that depressions are frequently misplaced in the UM analysis field as compared with satellite imagery and the associated conceptual model. This error can consequently be amplified as it can result in an error in the track and intensity of the depression.

The essence of conceptual models is that they provide a concise means of breaking down a weather system into its component elements. Each of these elements has well defined properties and positions in relation to the other components of the system. It is on this basis that conceptual models provide a powerful tool in the verification and diagnosis of Unified Model fields, whether they be analysis or forecast fields, or modified fields created by new data assimilation techniques (e.g. PV modification).

Figure 2 illustrates how each component of the conceptual model may be represented in the UM. In the example, the cloud system itself may be observed by many different types of satellite imagery – e.g. water vapour imagery is shown here, but equally infra-red imagery could have been used. The jet streaks[2] J1 and J2 in the upper troposphere may be clearly identified as localised regions of high winds.

[2] Jet streaks are relatively short lived cores of intense winds (see isotach pattern in Figure 2) within the large scale jet stream running through a synoptic scale upper trough (see e.g. Semple (1998)). Conceptual models

of developing into a leaf cloud – a classic signature in conceptual models of cyclogenesis (see e.g. Bader et al (1995)). To the rear of J1 is the leading edge of a second jet maximum, jet J2. Associated with the left exits of both jets are two high PV regions. The PV maximum to the north of J2 is particularly important in conceptual models terms, as it is this which will later evolve into the dry intrusion airstream – a major airflow in a midlatitude cyclone without which a cyclone will rarely develop to any great degree.

Thus the UM analysis and the conceptual model analysis are in disagreement. Some indication of the accuracy of the UM analysis may be suggested from the resulting forecast, since errors in the initial conditions of a forecast will have a significant effect on its outcome.

The 30 hour forecast (when the cyclone is mature) resulting from the analysis shown in Figure 3 is illustrated in Figure 4. In the UM forecast, there are signs of jet streak J2 in the vicinity of the cyclone area, but its extent is in error when compared with the conceptual model treatment. Also, the dry intrusion airstream associated with jet J2 is not large enough, nor in the correct position. Since J2 and the associated high PV is so influential in the system, this has a significant effect on the severity of the cyclone that the model forecasts: 997mb depth is forecast for this time as opposed to 988mb in the analysis. The location and orientation of Jet J2 is also related to the position of the surface low centre. A comparison between the top and bottom images of Figure 4 shows that the forecast position is approximately 200 km further east than its analysis position at the corresponding time.

The next section takes the basic principles discussed here and develops them into a versatile conceptual model framework for UM diagnosis.

2.2.2 A Conceptual Model Diagnostic Procedure

The case to be studied as an example is a cyclone that developed in the south western Atlantic on the 23rd December 1997. As early as 6z on this day, the satellite imagery was indicating pronounced signs of cyclogenesis with the appearance of a developing cloud head. The system developed rapidly as it moved north eastwards towards the UK and was responsible for particularly strong winds with gusts approaching 100mph on the west coast during the 24th December 1997.

The conceptual model procedure developed here breaks down the UM field into key component elements of conceptual models. This has the immediate advantage that individual physical processes are identified from the outset, thereby enabling the origins of forecast errors to be readily identified. The components used are:

1. Red contour - PV on a 300mb surface with a value of 6 pv units.
2. Red arrow - Axis of wind speed on a 300mb surface with an intensity greater than 55 m/s.
3. Gold arrow - Axis of maximum θ_w on a 900mb surface.
4. Blue contour - PV on a 900mb surface with a value of 0.6 pv units.
5. White circle -The location of the surface low pressure centre.

Items 1 and 2 in the above list relate to upper level forcing of the cyclone - item 1 indicates the presence of a high PV anomaly with item 2 representing the associated jet streak. Both these items are crucial to the development of a dry intrusion within the cyclone. Items 3 and 4 in the list relate to lower level forcing of the cyclone - Item 3 indicates the axis of the W1 warm conveyor belt at 900mb, and item 4 relates to the diabatic production of PV principally associated with rapid ascent within the W2 warm conveyor belt.

gradual deepening for the following 12 hours, and a period of rapid deepening after t+18. Again, this is consistent with the results of the conceptual model procedure - little or no development in the first 6 hours followed by development of low level PV at t+12. At t+18 the system initiates upper level development (shown by the appearance of an upper level PV anomaly), the coupling of which with the low level features results in the period of rapid deepening at this time.

In summary, the conceptual model diagnostic developed here points to a significantly different forecast low than was actually observed to develop in the analysis. The results suggest the forecast developed an upper level forced system in association with a large upper level PV anomaly present in the analysis time. The analysis however illustrates a low that developed initially through low level development in association with the pre-existing warm conveyor belt present in the analysis time. The analysis system was then observed to develop explosively through an initiation and coupling with upper level PV anomalies absent in the initial analysis time. This leads one to ask the question as to why the UM developed an entirely different system, and suggests an error in the initial analysis field.

The analysis fields may be verified against satellite imagery using conceptual model analysis and is presented on the map of Figure 5. The red circles indicate the position of the surface low pressure centre in the UM analysis field. This may be compared with the orange circles which indicate the location of the surface low when deduced from infra-red satellite imagery and the appropriate conceptual model. It is clear from the comparison that the initial model analysis is incorrect, and that the model analysis remains significantly poor until time position 4 or 5 (within a reasonable error margin).

The track of PV entities A and B identified in the conceptual model diagnosis of the forecast are also presented on the figure. It can be seen that PV entity A in the forecast (green circles) has a track which lies closer to the true track of the storm (which developed in association with PV entity B). This is an interesting result since PV A in the forecast corresponds to the low level development of the left hand warm conveyor belt - the development of which in the analysis was observed to lead to the true Christmas eve storm. This suggests that the model forecast developed the correct low level development (PV entity A) in association with the existing warm conveyor belt, but that through a poor analysis at time 1, developed a second low level feature (PV entity B) in association with the incorrectly positioned low centre. The difference is then a forecast that develops an upper level forced cyclone too far to the west, as opposed to a lower level forced cyclone further to the east.

There is much more to be learned from this case analysed with the conceptual model procedure that is not discussed here. However, it is hoped that it illustrates how a method of verification could be applied using conceptual models. The verification of model fields using conceptual models in this way may be used to analyse model structures at any stage in the forecast process: verification of analysis fields, forecast products, data assimilation procedures and PV modifications (see later sections) requires no alterations of the basic verification process described here. Also since conceptual models embody the physical processes which are evident in the structure of the cyclone, the *verification technique may also be used as a tool to guide model development* in areas where UM products do not correspond with the conceptual model analysis.

2.2.3 UM Conceptual Model Skill scores

Skill scores are currently produced for the UM as a measure of its performance and are useful in determining the impact new developments make on the forecast – i.e. if they have a positive or negative effect. These skill scores are currently based on differences between

forecast quantities and observed quantities such as near surface temperature and wind speed.

The previous section illustrated that conceptual models may be used in conjunction with satellite imagery to identify key aspects of a cyclone's structure and thus provide a means of identifying errors within the NWP product. A closely related potential application would be not only the identification of the model error but the subsequent production of a skill score based on the conceptual model verification so as to identify where and under what circumstances errors occur.

This would not be an easy system to develop since it amounts to a comparison of interlocking components each having degrees of freedom in space and intensity (compare forecast and analysis panels on Figure 5). A skill score based on these patterns of components therefore depends on a match between a conceptual model treatment of analysis fields and the conceptual model treatment of forecast fields. However, if the conceptual model breakdown of the system is viewed as something akin to a 'fingerprint' of the system, then it is perhaps an indication that the production of algorithms to perform this task could be written and used in an operational sense to produce a skill score. This could conceivably lead to either an operational system in which the forecaster was warned of a deviation from conceptual model behaviour (and thereby the possibility of a bad forecast) or a developmental system where a database of UM inaccuracies could be assembled to identify where research is required.

When used alongside the existing skill score technique, this process not only gives an indication of the performance of the model, but also indicates *why* the performance is good or bad: since a conceptual model skill score is directly related to the structure and physical processes occurring within a weather system.

2.3 Operational Applications of Conceptual Models in NWP

2.3.1 Interpolation of sparse observational data

The observational network varies in its density from place to place over the globe such that the density is high over Europe, but relatively low over the Atlantic. This is of particular importance as the western Atlantic is a breeding ground for many extra-tropical cyclones which reach maturity near the UK. The result is that many cyclones over the UK are forecast inaccurately or not at all in their early stages and that one or two days' warning of significant events may be lost.

It is suggested that conceptual models may therefore be used to interpolate between observations in regions of sparse data, thereby effectively increasing the representation of a system in the analysis field.

Figure 7 illustrates how the interpolation process could work. The figure shows a hypothetical situation with surface observations shown as yellow circles, and the conceptual model of a cyclone which has been identified in that location using a satellite image. Note that the conceptual model airflows are system relative - the relationship between these and the surface observations being the addition of the cyclone's velocity. A surface observation (and therefore relative to a buoy for example) of warm, moist air at the surface with westerly winds at one point, with much colder easterly winds to the north east at another point would ordinarily be two completely unrelated readings. However, when used in conjunction with a conceptual model, the region of influence of each point may be altered within a physical basis. The warm air observation to the south could be added with a weighting so that it extends northwards, rather than assuming a circular distribution of

by natural progression that the process may be continued in the application of conceptual models to the UM.

Bogus observations may be input to the UM by forecasters who notice discrepancies between the model output and satellite imagery. These observations are invented by the forecaster and added to the original set of 'real' observations. The aim of this *analysis* is to incorporate into the model real systems that may not be represented well or at all in the original model field. This process therefore requires human intervention and human interpretation in a process that is otherwise largely automated and is therefore open to the introduction of data that does not represent physical systems well. It is also common that the forecaster has to be somewhat 'heavy-handed' in their introduction of the bogus observations in order for the model to accept them.

Consider a satellite image of the Atlantic Ocean, with various cloud structures visible and in a situation similar to that shown in Figure 7. Suppose that in this hypothetical case there are no observations present in the location of the weather system so that the data assimilation process is unable to represent any structure whatsoever in the model field (the probability of this situation increases with smaller systems such as polar lows or less developed systems than that shown). The cloud structure visible on the satellite image will be identifiable as a cyclone in a particular stage of evolution that can be described by a conceptual model. On a purely manual basis, the forecaster could analyse the satellite imagery, and then introduce a conceptual model of the cyclone at the correct stage in its evolution – effectively adding a consistent three dimensional structure to the model field. The use of conceptual models in this way could provide some degree of quality control, as the bogus data could be checked against (and adjusted with) conceptual models of systems being introduced.

This link between satellite imagery, conceptual models and the bogussing of data to improve analysis fields has been explored by Grant and Bader (1994). In their study, Grant and Bader used satellite imagery to determine the airflow properties within systems that were incorrectly represented within the model analysis. In their first case (of two), bogus data were incorporated as winds and relative humidity values to simulate the warm conveyor belt of the conceptual model inferred from the satellite imagery. They report that the revised forecast agreed better with the observations than the original forecast. In their second case, Grant and Bader identified a mid-level cloud extrusion on the satellite imagery which is explicitly dealt with in conceptual models (see e.g. Bader et. al (1995) and Semple (1998)) and therefore determined that lower levels would be influential in the evolution of the system. As a test, they used the lower level fields from a later model run (i.e. fields which will better represent the structure signalled by the conceptual model) and incorporated them with the upper fields of the earlier forecast. The result was a forecast (with the original time as a starting point) that predicted better the heavy rain observed at the time.

Providing that the initial step of the recognition of a cloud system as an evolutionary stage of a cyclone could be done automatically, conceptual models could be used operationally to convert the image into a three dimensional structure composed of relatively precisely defined airflows. This structure should then be what the model would have generated if it had predicted the cyclone in the forecast or what it would have had in the case of a good analysis. This process could be extended to involve other forms of satellite imagery and increase the accuracy of the model representation. For example, infrared imagery gives more information on cloud heights and temperatures (see Sec. 2.3.3 for a good example of this), whilst water vapour imagery gives information about the J2 (dry intrusion) jet stream. This is clearly more complicated than the system requiring forecaster intervention as the task of automatic image recognition would be formidable. However, it may be possible that neural networks could be trained to recognise conceptual model-like weather systems.

The assembled components then provide a three dimensional structure for the system in terms of pressure, temperature, wind speed and PV. These quantities may be treated as observations and assimilated into the model just as real observations are assimilated.

The analysis field at the bottom of Figure 8 is included to indicate how a UM field relates to the conceptual model components. In this particular case, the analysis field was reasonable, with the conceptual model components represented fairly well within the analysis. A comparison between the conceptual model treatment (top) and the UM analysis (bottom) suggests that Jet J2 could extend further north towards the low centre and J1 is slightly misplaced to the south east. The PV anomaly at 300mb is reasonably well placed, although there is the ambiguity of the second PV anomaly slightly further to the south west. Despite these slight errors, the comparison illustrates how a new analysis field could be generated from a satellite image and an appropriate conceptual model. If possible, the assimilation of satellite imagery in this way would greatly reduce the problems of insufficient observations over the Atlantic, and lead to earlier and better forecasts of cyclones before they reach the UK.

Conceptual models treat component elements *relative to one another* and so for them to be of any use operationally, at least one property must be known quantitatively. However, providing some idea of the average temperature (say) in the vicinity of the developing cyclone is known (even if it's a large scale distribution in the Atlantic) then the quantities of other components scale accordingly. For example, if the wet bulb potential temperature at 900mb to the south of the developing cyclone being assimilated is 17°C then this would be a good starting point for the wet bulb potential temperature of the warm conveyor belt. The cold conveyor belt is then characterised by values several degrees lower (10°C say) and the W2 flow (the lower part of the warm conveyor belt feeding the cloud head (Young et al., 1987 and Semple 1998)) only a few degrees lower (15°C say).

The link between the conceptual model, satellite imagery and model fields is in effect a two way process. One can start with a satellite image, impose the conceptual model, and then deduce a model field (this section), or one can start with a model field, deduce the conceptual model and compare it with the satellite image (Sec. 2.2.1). This process is made more reliable for NWP purposes due to the fact that conceptual models have NWP processes incorporated into them at their origins (see discussion in Sec. 1.4). The result is that the conceptual model inferred from satellite imagery has at least the resolution of NWP products, and is therefore of sufficient precision for model requirements.

2.3.3 Enhancement of mesoscale structure

Conceptual models allow the breakdown of synoptic scale systems into the more fundamental elements of conveyor belts. These conveyor belts may then describe systems on a more localised scale a hundred or less kms across. Synoptic scale information may therefore be enhanced on the smaller scale by the application of conceptual models. Thus although the UM may correctly represent the broad dynamical and thermodynamic fields associated with a synoptic scale extra-tropical cyclone, it is with the application of conceptual models that forecast enhancement and predictions about more localised weather can be obtained.

An example of how enhancement of mesoscale structure may be achieved is illustrated in Figure 9. The visible satellite image shows a frontal cloud band extending over much of the UK and towards northwest Spain. The infrared satellite image then indicates further structure to the frontal zone south of the UK, with higher cloud at its leading edge followed by lower cloud behind. By the use of the conceptual model, the satellite imagery of a system implies much about the vertical structure of the atmosphere along the entire length of the front: dry air from the middle troposphere with a horizontal velocity larger than that of

between cloud boundary sharpness, jet streak strength, PV gradient strength and PV maximum. Also, the rate of change of water vapour radiance in the dry intrusion region corresponds to the rate of descent of the tropopause depression. These factors would be great assets to PV modification techniques since although the correspondence between PV and water vapour imagery is fairly good in terms of positional correlations, it is much more difficult to infer the intensity of PV anomalies from the water vapour image.

Using the principles described in this section, conceptual models could provide a way of reliably determining the upper tropospheric air distribution and this could then be converted into PV fields ready for a consistent inversion back to wind and temperature fields.

2.3.5 Conceptual model enhanced PV modification - assimilating low level development

The PV modification technique described in the previous section deals with getting the *upper level forcing* of cyclogenesis correct. The method is inherently restricted to upper levels of the troposphere since water vapour imagery used in the PV modification process only provides information about these layers. In practice however, cyclones may develop by *lower level forcing* or by a *combination of upper and lower level forcing* in varying degrees. As discussed above, the PV inversion technique can only hope to improve the forecast in cases which are purely upper level forced or in which the error is entirely in the upper level forcing (see Sec. 2.2.2 for an example of low level development initiating cyclogenesis). It follows that since it is recognised that a coupling arises dynamically between the upper level PV and the lower level temperature gradient in extratropical cyclones, it is crucial in any analysis field that both upper and lower level fields are correct.

The importance of taking account of lower level development in the context of PV inversion has been investigated by Mansfield (1996). In his studies he reports that on several occasions the initial development is essentially initiated by low-level warm advection and it is the low-level cyclone that creates the upper anomaly. He concludes by stating that in cases such as these, the PV fields will not reflect the development until the low-level feature has distorted the upper-level PV gradient so that comparison with water-vapour imagery would be inadequate (PV modifications made to the Christmas eve storm discussed in Sec. 2.2.2 failed to make any impact on the forecast detailed (Swarbrick (1998)).

It is therefore proposed that conceptual models may be used to provide a way of modifying the lower levels of the atmosphere thereby complementing the PV modification process of the upper troposphere and providing a modified field of the entire troposphere. Figure 12 shows PV on the 300mb, 500mb, 700mb and 900mb surfaces and may be thought of as ascending through horizontal sections in a situation similar to Figure 11. The general trend when ascending through these sections is a shift from low PV at lower levels (tropospheric air) to high PV at upper levels (stratospheric air). However, the developing cyclone retains its separate PV identity throughout its vertical structure. The main cloud body (the larger component of the conceptual model framework indicated in Figure 12) is observed to show up as a region of high PV (embedded in a background of low PV) at 900mb where the warm conveyor belt W1 is beginning its ascent (the reasons of which will be discussed shortly). It is of particular significance that the cyclone develops at the northern end of this high PV region (Browning and Roberts, 1994) such that the PV maximum develops and intensifies with time at the location of the low centre as the cyclone evolves but diminishes at the southern end of the conveyor belt. As one ascends to 700mb the high PV region occupies a more northern part of the cloud system and indicates the fact that as W1 ascends slantwise it also travels northwards.

3. Conclusions & Future Work

This report has aimed to address the question of the possibility of conceptual model applications in NWP with a view to improving Unified Model performance. Its main structure was to perform thought experiments regarding any proposals and to determine if conceptual models were suitable and if the proposal was feasible/worth while.

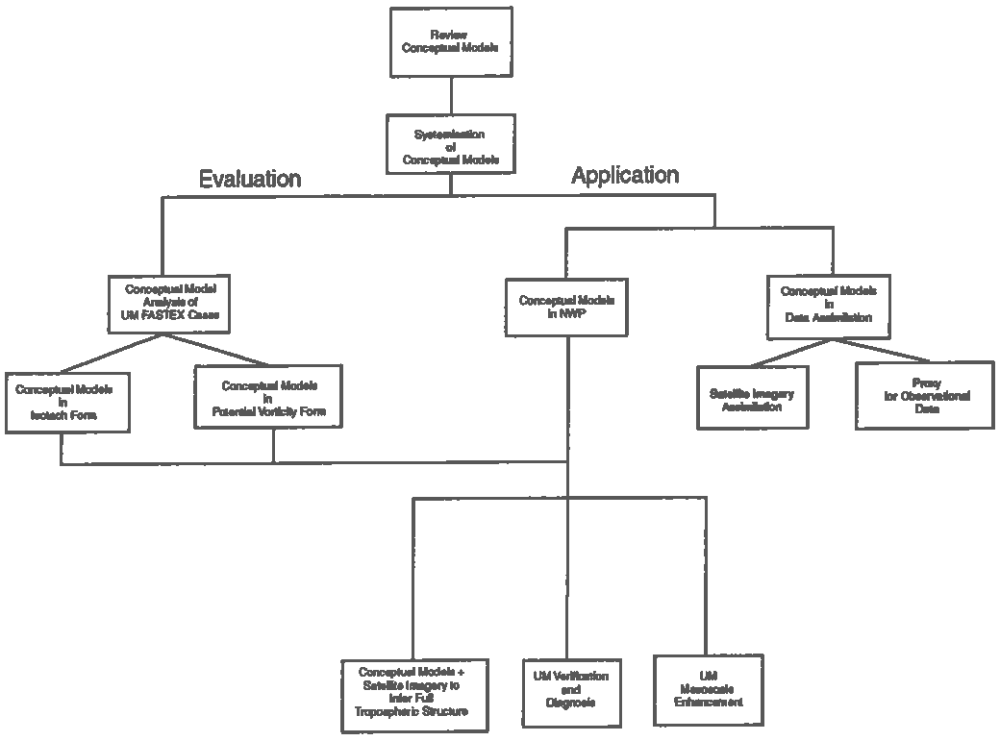

Figure 14 Diagram illustrating the steps made (from top to bottom) in producing the material for this report. An extensive review and systemisation of conceptual models (Semple, 1998) provided the foundation for the present work. Evaluation of conceptual models and their usefulness to NWP was performed by extensive analysis of FASTEX cases and this work enabled suitable formats of conceptual models to be established. Applications were proposed on two areas: in NWP and data assimilation.

The findings of this report may be summarised thus

- Conceptual models provide a versatile way of analysing a weather system via ***relatively precisely defined component elements***.
- The components of the conceptual model may be analysed by a variety of diagnostic variables and the relationship between the conceptual model and the unified model field is ***reversible*** in that it is valid whether converting conceptual models to NWP products or vice versa.
- Conceptual models provide a ***qualitative diagnosis tool to aid in the development of the unified model*** by graphically representing physical phenomena that are present in all cyclones. In this way a ***Unified Model field may be verified, diagnosed or corrected***.
- Once broken down into its component elements, each weather system has a ***conceptual model 'fingerprint'*** which could be used to produce a ***quantitative performance indication of the UM*** for that particular case.

- Because of their visual nature, conceptual models may readily be used to relate satellite imagery to a consistent three-dimensional atmospheric structure so that the ***assimilation of satellite imagery*** is feasible.
- When used in conjunction with satellite imagery, conceptual models are a ***proxy for observational data*** and may be used to enhance the observational network in data sparse regions.
- Conceptual models provide a ***comprehensive description of the upper troposphere during cyclogenesis.*** This information allows more accurate PV modifications to be made on the basis of water vapour imagery.
- The ***potential vorticity modification technique may be enhanced by conceptual models*** of weather systems to allow a description of the entire troposphere within a developing cyclone. This facilitates ***successful PV modification of more cyclogenesis cases*** - i.e. cases that are not entirely upper level forced or cases in which the error is not entirely in the upper levels.

This preliminary study therefore suggests that despite the problem of automating the procedures outlined above, there is great potential for conceptual model application in NWP and prompts further investigation into one or more of the aspects discussed. Of particular interest are the applications concerning 'conceptual model diagnostics' and 'conceptual model enhanced PV modification' (Secs 2.2.2, 2.3.4 and 2.3.5). These applications are preferable because they require only a moderate degree of development before their operational application.

Conceptual model enhanced PV modification requires a better knowledge of the internal PV structures of cyclones if it is to be at all reliable. In view of this, the author is intending to conduct a study on various cyclone types to determine the possible orientations and structures of PV within midlatitude systems.

It is envisaged that the conceptual model diagnostic procedure developed here will not only aid in the verification of model fields but also in the testing of assimilation procedures and in the testing of PV inverted fields.

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